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DESIGN STUDY OF A SATELLITE PHOTOMETER

Prepared for
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION
Washington 25, D.C.

Contract NAS 5-1170

EOS Report 1830-Final 15 June 1961

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ELECTRO-OPTICAL SYSTEMS, INC. Pasadena, California

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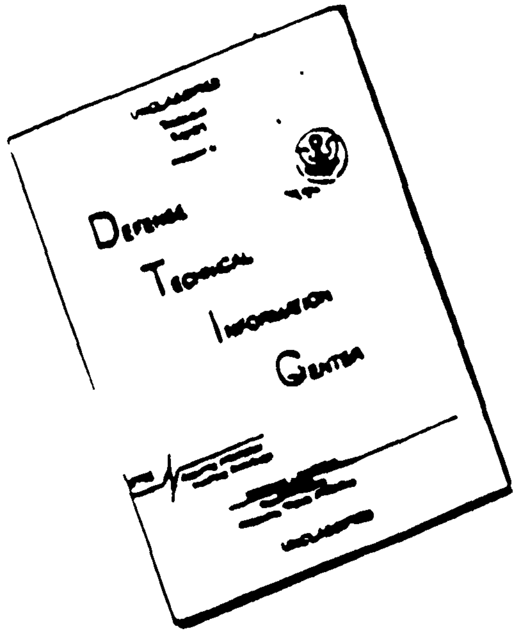

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Prepared by the staff of the

ADVANCED ELECTRONICS AND
INFORMATION SYSTEMS DIVISION

Approved by

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CONTENTS

1. INTRODUCTION

This report summarizes a short design study conducted by Electro-Optical Systems, Inc. on an instrument to make photometric measurements from an earth satellite vehicle. The original experiment was proposed by Dr. William A. Baum of the Mount Palomar Observatory Staff (Refs. 1, 2). The history of this particular project will not be reviewed here although there has been considerable interest of late in producing a photometer that will measure combined extragalactic light night airglow as part of the experiment. The combination of the two scientific experiments may be possible with certain mechanizations that have been suggested. Some types of satellites utilize spin stabilization for attitude control. Such a device spends a good portion of its operating lifetime looking at the earth; if a photometer is carried for observation of extraterrestrial light, then it might be very possible to use the same instrument for observation of events taking place in the direction of the earth.

This study covers some of the possible satellite vehicles on which a photometer might conceivably be carried and a possible mechanization for a particular satellite vehicle is suggested as part of this report. Since there are so many possible combinations of vehicles and situations for which the instrument might be designed, it was not possible to investigate in depth all the various combinations that might be involved. On the other hand, a mechanization is suggested which would work on one of the Orbiting Solar Observatory satellite series. With simple modifications the same instrument could be adapted to a totally stabilized geophysical satellite, such as one of the Orbiting Geophysical Observatory series. A design has been formulated using the various components of a photometer instrument which will constitute a workable system to perform significant experiments in both the astronautical and geophysical disciplines. A detailed design and development effort is required to translate this concept into flight hardware.

The scientific objectives of the experiment will be briefly described in Sec. 2. A summary will be given of some of the types of vehicles on which this instrument can logically be carried and a recommendation as to an assignment in a specific configuration. The gross design of an instrument which could fulfill these objectives is then developed and explained. The many crucial features such as the optical and detection system, the electronics, the mechanical structure, the data conditioning equipment and the interface considerations will be described in general form and the necessary design, development, fabrication and testing efforts are set forth. Some thought has been given to the data recovery, data reduction and data analysis phases of the eventual program.

2. REVIEW OF EXPERIMENT OBJECTIVES

The integrated light received at the surface of the earth on a clear moonless night can be ascribed to four general sources:

1. Radiation (airglow) emitted by the earth's upper atmosphere
2. Zodiacal light
3. Light from objects within our own galaxy
4. Light from beyond our own galaxy

All these sources are appreciably scattered and attenuated by the earth's lower atmosphere.

The airglow, which originates in a layer about 100 km above the earth's surface, is auroral in nature and consists of an emission spectrum. The brightness of this airglow is patchy and is continuously varying; substantial changes can occur in a matter of minutes. In general, the brightness of the airglow tends to increase with increasing angle from the zenith as a result of the increasing length of path through the emitting layer. As the horizon is approached, however, the brightness decreases again because of atmospheric extinction (attenuation), and a band of maximum intensity remains about 10^{o} above the horizon.

Since the zodiacal light is merely sunlight scattered by particles in the solar system, its spectrum is primarily like that of the sun. Although much of the zodiacal light is concentrated along the ecliptic, where it is visible near the horizon just after evening twilight and just before morning twilight, polarization measurements show that fainter parts of this light extend over the whole sky. Faint features include the gegenschein diametrically opposite the sun and the recently discovered querschein at the pole of the ecliptic. In general, the distribution of zodiacal light is a function of solar elongation and celestial latitude.

The integrated light from objects within our own galaxy represents a composite of many different spectra. The over-all average spectral quality, however, is not greatly different from that of sunlight. There is evidence that star counts alone do not account exactly for all the light in the galaxy, particularly in the galactic plane (i.e., in the Milky Way). The balance is presumably the result of nebulous sources and interstellar scattering. The distribution of the light of the galaxy is primarily a function of galactic latitude with a lesser dependence on galactic longitude. In high galactic latitudes, in which the galaxy is faintest, its integrated surface brightness is of the order of 6th magnitude per square degree, which is about 2 magnitudes fainter than the airglow and zodiacal light.

The integrated light received from objects beyond our own galaxy is the quantity about which we know the least, but it is, philosophically, the most interesting because its brightness and color provide in principle a means of distinguishing cosmological models, that is, of determining whether we live in a finite or infinite universe (Ref. 2). For example, if we lived in the simplest kind of universe imaginable - ageless, infinite, Euclidean, and non-expanding - the brightness of the entire sky should be nearly infinite and we should all be incinerated. Since this is not the case, the universe is obviously not of that type. Counts of remote galaxies indicate that their integrated light out to the photographic limit of the 200-in. telescope should be in the neighborhood of 8th magnitude per square degree in the red and infrared parts of the spectrum. On the basis of present material, it is not possible to say how much additional light comes to us from beyond that range or to state exact spectral distribution. We know only that it should be extremely red. The cosmological question hinges mainly on the spectral distribution of the extragalactic light; its total intensity should then tell us how much luminous matter there is in addition to that which is concentrated within observable galaxies.

Light from all four sources - the airglow, the zodiacal cloud, the galaxy, and the extragalactic universe - must pass through the earth's lower atmosphere in order to reach instruments at, or near, the earth's surface. Rays of light arriving from various directions are not only attenuated by the atmosphere but also are diluted by light scattered out of rays originally arriving from other directions.

Some attempts have been made to disentangle the airglow, the zodiacal light, and the light of the galaxy (Refs. 3, 4, and 5), but the problem is a very difficult one to solve. If the earth's atmosphere could be completely eliminated, the situation would be greatly improved. Moreover, there appears to be very little chance of distinguishing the extragalactic contribution, which is the weakest of all, unless observations can be made from an instrument located outside the earth's atmosphere for a substantial length of time. Observation of the extragalactic contribution from the earth's surface is probably out of the question; from an artificial satellite, there is a reasonable chance.

It is difficult to judge in advance the value of an exploratory experiment of this kind. Given a satellite of limited capacity for astronomical purposes, the proposed experiment is a natural first step. Extraterrestrial photometry of the zodiacal cloud and of the galaxy, as well as of the airglow observed from above, would be of unquestioned interest. Mapping of the galaxy in the extraterrestrial ultraviolet region is of great interest also, and if, by good fortune, a definitive result should be obtained on the cosmological question, the experiment would be of great significance and a scientific landmark.

3. PROGRAM RECOMMENDATIONS

Conversations have been held with various persons who were associated with the satellite photometer experiment or with the general NASA astronomy and astrophysics program to tabulate and consider the various experimental situations in which this instrument might be involved. A considerable amount of correspondence with Dr. Baum has taken place in which technical details were explored concerning the instrument itself. Conversations have been held with Dr. Roach of the National Bureau of Standards, Boulder, Colorado, with various individuals of Ball Brothers Research Corporation in Boulder, Colorado, with Dr. Lindsay and Dr. Kupperian of the Goddard Space Flight Center, Dr. Nancy Roman of the National Aeronautics and Space Administration, Dr. Herbert Fredman of the Naval Research Laboratory and with Dr. R. Davis of the Smithsonian Astrophysical Observatory. These conversations will not be reported in detail here, but numerous helpful suggestions were obtained from all of them. Discussions concerning possible rocket flights were held with Dr. Roman, Dr. Lindsay, Dr. Kupperian and Dr. Davis as well as with Dr. Phillip Fisher of the Lockheed Missile and Space Division, Palo Alto, California.

3.1 Satellite Vehicle

It is recommended that an instrument be developed for the S-16A type satellite configuration, where orbit, stabilization system (providing automatic scan through the spinning wheel), and data handling system are very well suited to the combined astronomical and geophysical experiment. The mechanization is reasonably straightforward and indications seem to be fairly strong that a follow-up satellite (S-16B?) will be authorized and have several experiments assigned to it.

The detailed engineering design and prototype fabrication should be started fairly quickly so that a rush schedule will not be necessary once the decision to proceed is obtained. The basic design of the instrument and associated electronics is not very dependent upon the spacecraft in which it is installed. The detailed mechanical envelope in some portions of the data handling system is sensitive to the specific vehicle and its characteristics; however a good portion of the design would be done independently of the specific flight assignment. The most serious change that could be anticipated would be the installation of the instrument into a non-spinning satellite, in which case some sort of scanning system might have to be incorporated.

3.2 Rocket Test

It is also strongly recommended that a simple instrument be prepared for early test flight in some sort of rocket vehicle. There are several Aerobee rockets scheduled for the latter part of this year, any one of which might be available for such a simple task. This task could check out the basic instrument itself including the optics, photomultiplier, light chopping device, amplifiers and storage units. It would also provide very valuable information on the range of intensities encountered within the spectral and spacial restraints placed upon the entrance to the detector system.

Suggested mechanizations for both the S-16A type of satellite configuration and for a rocket instrument are contained in the last sections of this report. Some of the details of these mechanizations are included as a technical appendix of this report.

4. MECHANIZATION FOR S-16A TYPE SATELLITE

The following brief description represents a possible mechanization for the satellite photometer experiment. This particular mechanization is for use on an S-16A type satellite, one of the orbiting solar observatory series. As presently conceived, the instrument comprising the photometer and associated electronics could be used to perform both an astronomical and a geophysical experiment. During a portion of its operating cycle, the photometer would scan the extraterrestrial sky. While the instrument is pointed at the earth, it could also be used to observe night glow phenomena on the dark side of the earth.

4.1 General Description of Mechanical System

The S-16A satellite has two major mechanical sections. One section (called the sail) is oriented when in sunlight so that it directs the normal to its surface toward the sun to enable instruments to operate while pointed in the direction of the sun. The other portion of the satellite is called the "wheel"; the sail is attached to a bearing in the center of the wheel and the wheel is caused to rotate at approximately 30 rpm to provide directional stability. Since the vehicle is stabilized so that the normal from the sail always points toward the sun, the wheel will rotate in such a direction that its plane always includes the sun. The wheel is made up of segmented compartments each of which can carry an instrument that can be allowed to look through the outer surface of the wheel.

The photometer instrument as presently conceived would employ a system of fixed optics mounted opposite an aperture in the exterior surface of the wheel. The acceptance cone of the photometer would rotate with the wheel at an angle 10° to 15° away from the plane of the wheel. This would insure (once stabilization has been achieved) that the optical system could never look directly at the sun. It is suggested that the optical system be composed of reflecting elements and that a filter disk similar to the original experiment be used so that several different wavelengths can be observed. The filter disk would carry three filters as well as calibration devices.

It is suggested that logarithmic compression be used to provide higher accuracy at the low end of the photometric response of the instrument. At the same time, sufficient dynamic range should be provided that the brighter portions of both the zodiacal light and the night air glow will not saturate the instrument. This portion of the circuitry has been considered in some detail by Butler and Brantner of JPL.

Data Handling System

A data handling system is suggested here which would digitize, store, and transmit the readings to the satellite tape recorder. The S-16A satellite will use a digital data handling system that is based on 16-16 bit words per frame with a frame repetition rate of 0.64 seconds. The tape recorder records continuously in this mode until playback is initiated, when it is speeded up to compress the data from the preceding orbit into a short transmission time. Some of the earlier mechanizations tried in the process of formulating this one involved the synchronizing of the data conditioning equipment in the photometer to the rotation of the wheel. This added many unnecessary complications and the mechanization here is one based on synchronization of the measurements with the data system rather than the wheel. It is felt that the phase relation between the frame rate and the data handling system and the position of the wheel can be obtained by use of the data itself. This will be seen later.

The wheel rotates once every two seconds; the data system has a frame length of 0.64 seconds - this means that 3.13 data frames pass per satellite revolution. Two modes of operation are proposed, one on the dark side of the earth and one on the sunlit side of the earth. For the sake of discussion, consider the operation on the dark side of the earth first. Most of the instruments in the satellite are not useful when the sun is not in view and it is possible to take over some of the data words that are normally used by the solar directed instruments. In particular, the data system has been mechanized so that the solar spectrometer uses every other word in the frame. It is apparently quite easy to divert these words to the use of the satellite photometer when on the dark side of the earth. If eight (alternate) words are available every data frame, then simple arithmetic shows that twenty-five data samples are possible each rotation of the wheel. It would be desirable to choose these words to occur at alternate locations, giving a symmetric 50 percent data duty cycle.

Parameters for Optical System

Some parameters for the optical system were arbitrarily chosen in order to perform first calculations on the data system. A field of view of approximately 8° for the full view angle and a shutter time of .020 seconds were chosen. The criteria for choosing these are discussed later but it appears that these are fairly good choices. With the night side operation, twenty-five samples of 8° each (slightly larger than 8° due to the smearing caused by the wheel rotation) results in a coverage of 200° of the 360° of each rotation. The samples will be symmetrically spaced and can be imagined radially directed such as the spokes of a wheel. The optical system can be briefly explained as follows:

An entrance aperture approximately 4 inches in diameter is provided in the exterior wall of the satellite instrument compartment. A concave mirror placed in the bottom of the instrument compartment focuses the energy through the filter and falls on the face of the photomultiplier tube. It might be necessary to place a series of baffles in the entrance aperture to provide mechanical strength for the exterior surface of the satellite vehicle and to minimize the extraneous light that might enter the compartment, particularly in sunlight.

The filter wheel could contain three interference filters for the purpose of selecting the wavelength region to be scanned. The filter wheel would also contain one or more blank portions (during which time the photomultiplier tube dark current could be read) as well as one or two small radioactive light sources for calibration.

4.2 Electronic Subsystem

The operation of the instrument can be best described by reference to Fig. 1 which is an over-all electronic block diagram of the photometer instrument. The upper left hand portion of this figure indicates in schematic form the photomultiplier, amplifier, and power supply system. Although this is a complex and important subsystem it will not be dealt with further here. Most of the components in Fig. 1 are concerned with the instrument sequencing, data conditioning and data handling. A diode gate is used as an electronic "shutter" which allows the output of the photomultiplier tube to be averaged over the shutter interval in an integrating circuit. The output of the integrator is converted to digital form by means of the 40 kilocycle oscillator, stairstep generator, and comparator circuit. The operation is as follows:

The output from the integrator circuit is compared with the output from a stairstep generator. The stairstep generator is driven by a 40 kilocycle oscillator and produces a voltage that increases a certain increment with each output pulse from the oscillator. The comparator indicates when the stairstep output is equal to or greater than the signal appearing at the output of the integrator. Until equivalence is reached, the signal from the 40 kilocycle oscillator is allowed to accumulate in a binary counter. When equivalence of the stairstep output and the integrated signal is reached, the gate circuit allowing the 40 kilocycle signal to enter the counter

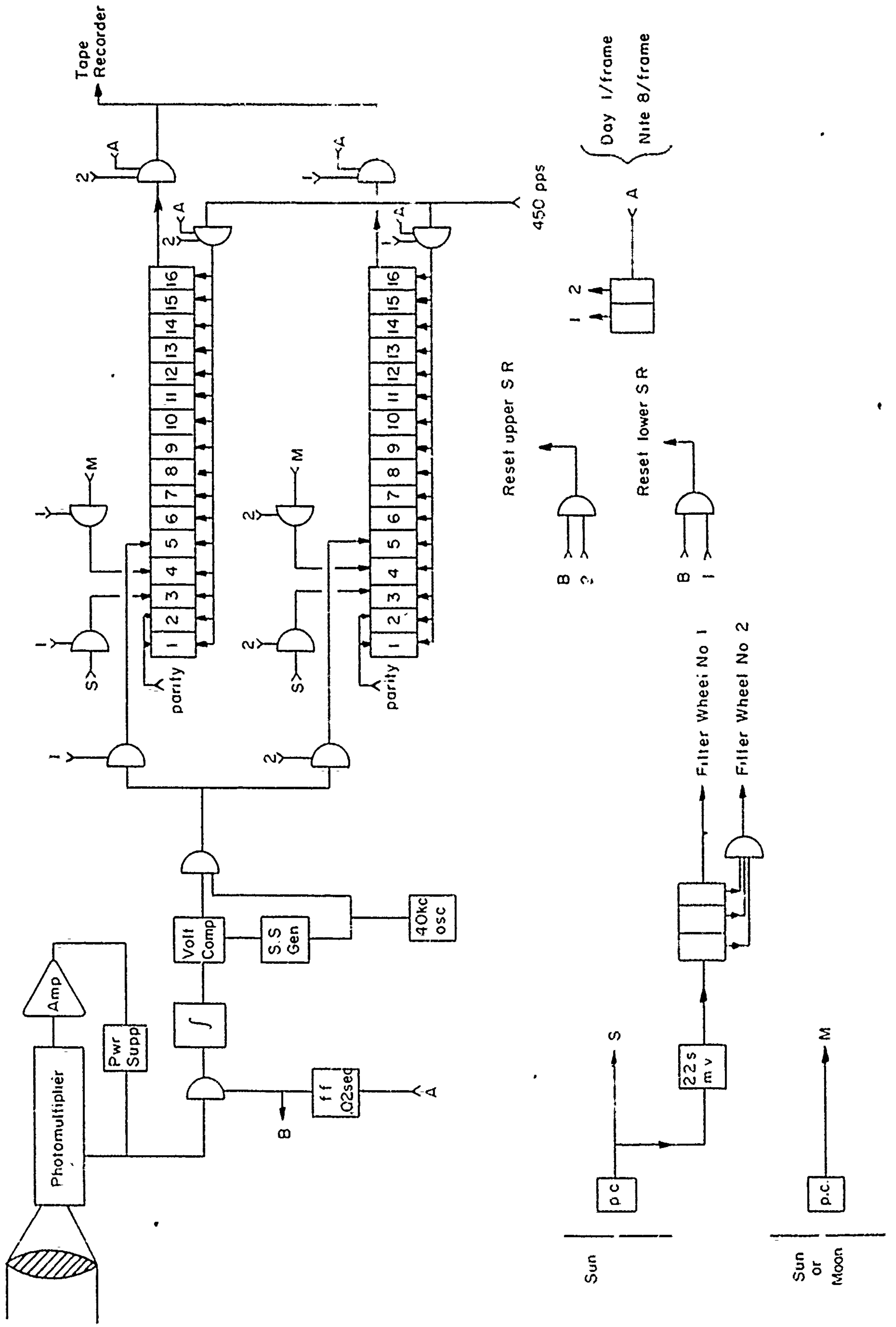

FIG. 1 PHOTOMETER DATA HANDLING SYSTEM

is interrupted and the number of counts present in the counter is an indication as to the voltage level of the integrator output.

Two separate shift registers are used, one of which receives the 40 kilocycle signal indicating the magnitude of a particular sample from the photomultiplier. The other shift register is used to transfer information into the satellite tape recorder at the same time. These two shift registers operate in opposition, one reading in, while the other reads out. A 16 bit shift register is used; some of the first few bits are reserved for special functions. The sequencing for these operations is controlled by the subsystem in the lower right hand corner of Fig. 1. A readout pulse is supplied by the satellite timer which is represented by circuit "A". This is a 35.5 ms pulse which occupies one full 16 bit word interval and which causes the data to be shifted from the instrument storage into the satellite tape recorder. For night time operation, the readout command is exercised every other word and the waveform consists of an unsymmetric square wave which is "on" for 35.5 ms and zero for 40 ms. This goes directly into a scale-of-2 circuit which alternates the operation of the two shift registers and their associated gates. The two possible outputs of this circuit are labeled "one" and "two". In the "one" position, 40 kilocycle pulses are allowed to flow into the top shift register during the accumulation period in the analog-to-digital conversion cycle. At the same time, the readout gates are enabled on the lower shift register which allow shift out pulses to actuate the appropriate inputs on the bottom of the register and which shift out the pulses to the satellite tape recorder.

At the close of the readout command from the spacecraft, the electronic shutter is caused to function by a pulse generated in a one-shot multivibrator which generates a 20 ms pulse following the trailing edge of the readout command pulse. This is used to open a gate circuit for the 20 ms period which allows the photomultiplier output to enter the integrator. The signal is stored there until the start of the analog-to-digital conversion step which is initiated by a combination of the spacecraft readout pulse (A) and one of the sequencing pulses ("one" or "two").

The 16 bit data word is longer than necessary to provide the desired accuracy for the photometer signal. Only twelve of the available data bits in each word are used to carry photometric data. The first two bits are reserved for a parity check to indicate possible errors in data transmission. The third and fourth bits are used to indicate synchronization between the data system and the rotation of the satellite wheel. Two types of position detectors are provided. These both consist of a small slit which scans the sky at right angles to the plane of the wheel. Each of these has a small photocell behind it, one of low sensitivity so that it responds only to the light flux available from the sun and the other of higher sensitivity so that it responds to light from either the sun or a partially illuminated moon. The gates for these signals are also connected to the sequencer for the instrument and the presence of a signal in just one of these channels would indicate that the moon was being viewed. A signal in both would indicate that the sun was being viewed at the instant that the photometric data was being read into the shift register. If neither the sun or moon are available, then synchronism can probably be obtained by study of the data itself. It should be possible to recognize the various features expected during a complete scan and to see the periodicity of these as the data is unfolded with time. The rotation of the wheel should maintain approximate synchronism with the rotation of the data system, frames, and correlation will only have to be determined rarely.

The operation on the sunlit side of the earth can also be described very briefly by analogy with that described for the dark side operation. The main difference in the operation is that the spacecraft data system will change so that only one word is used per data frame. This results in a slowdown of a ratio of 8-1 from that for the night time operation. Instead of twenty-five samples being taken per wheel rotation, 3.13 samples will be taken and the operation will be very similar to that previously described. When a readout pulse is obtained from the spacecraft, this will cause the analog-digital-conversion process to take place and it will also cause the reading out of the last data point taken (120° back instead of 16° of the wheel rotation). This will mean that fewer samples are taken when in the sunlight but that samples will be taken in this condition approaching within 10° of the sun or so. Also measurements can be made of the zodiacal light fairly close to the sun.

The satellite time standard is expected to be sufficiently accurate so that the time of each sample can be determined by counting data words backward in each data recording burst. The time of play-back initiation will be recorded in the telemetry station and that will indicate the time at which the last data word was recorded in the satellite tape recorder. The first word recorded in the full orbital data sequence will be identified timewise by the cessation of playback at the last telemetry recording station. With proper data reduction, it will be possible to determine the location of the satellite for each data word. The plane of the wheel can be determined by recourse to the data and the direction in space of each reading can also be determined. It will be most advantageous to mechanize all this in a computer.

The slit and photocell that detects the sun only is used to advance the filter wheel. A toggle action switch and motor is used so that one impulse is used (every 7th of each eight crossings of the sun) to advance the wheel to a calibration position. The other toggle position (every 8th of each eight crossings of the sun) advances the filter wheel to a filter position. The advance control mechanism uses a normally free running multivibrator with a 2.2 second period to advance the filter wheel on the dark side of the earth. This will synchronize at 2.0 second intervals when sun signals are received.

The filter wheel can be left in the dark current calibration position during launch and initial stabilization and another circuit added to allow the first movement of the filter wheel after regular sun signals are received. The instrument and satellite stabilization system are greatly simplified by the elimination of movable lenses and mirrors. With optics fixed in the satellite, approximately six months will be required to sweep out the entire sky.

4.3 Optical System

The purpose of the satellite photometer is to perform radiometric measurements of extraterrestrial radiation and of the earth's atmospheric airglow These two types of radiation may be characterized as extended sources of low radiance as seen from normal satellite altitudes, and both may be measured by the same type of photometer. The photometer will be used outside the earth's atmosphere onboard a satellite or rocket vehicle. The space allotted to the photometer onboard the vehicle will be arbitrarily chosen so that the analysis may have a starting point. The analysis and recommended design for the optical system of the satellite photometer described in the following subsection will include the target and extend to and include the photocathode interface.

4.3.1 Design Criteria

The ultimate optical design of the photometer will be based upon criteria determined by (1) the purpose of the instrument (2) the characteristics of the target, and (3) the nature of the environment. The design criteria of the photometer optical system are listed below:

Speed

Because the view fields of interest are extended sources of low radiance, the optical system must be quite fast in order that the detector (of a given sensitivity) may respond to the incident radiation. The parameters affecting the speed of the optical system are field-of-view, aperture, and transmission. A total field-of-view of 8° and a 4 inch aperture have been chosen for the photometer optical system. These values are not fixed but will permit a detailed preliminary analysis to be initiated. Actually, the above values are quite reasonable considering the measurements to be performed (field-of-view) and the expected compartment size onboard the vehicle (aperture). As a result, the only variable available to the optical designer which affects the speed of the optical system is the total transmission.

Space

Since the vehicle has not been chosen for the photometer experiments it is difficult to define the size of the photometer package. So that this analysis may proceed, the photometer compartment size is arbitrarily chosen (S-16a configuration) and is shown in Figure 2. The outside surface of the vehicle is represented by the 8 1/2 in. x 15 in. side of the compartment. The total photometer equipment, including the optical system, must be well integrated into the compartment space available. It is assumed that the photometer field-of-view is directed radially out from the axis of the vehicle.

Weight

Minimum weight of the photometer (and the optical system) is required without loss of reliability in performance.

Lifetime

The design of the photometer optical system must take into account the lifetime or duration of the experiment. In the case of a rocket-borne photometer, the lifetime may be a matter of minutes or hours whereas a satellite-borne photometer may be required to operate for months. The factors affecting the useful lifetime of the photometer optical system are:

a. Launch - The optical system must be able to withstand the high acceleration incurred during launch.

b. Intense Radiation Sources - The optical system (including the photocathode) must be protected against intense sources of radiation (such as the sun) entering the field-of-view of the instrument.

c. Erosion - The erosion of optical surfaces by

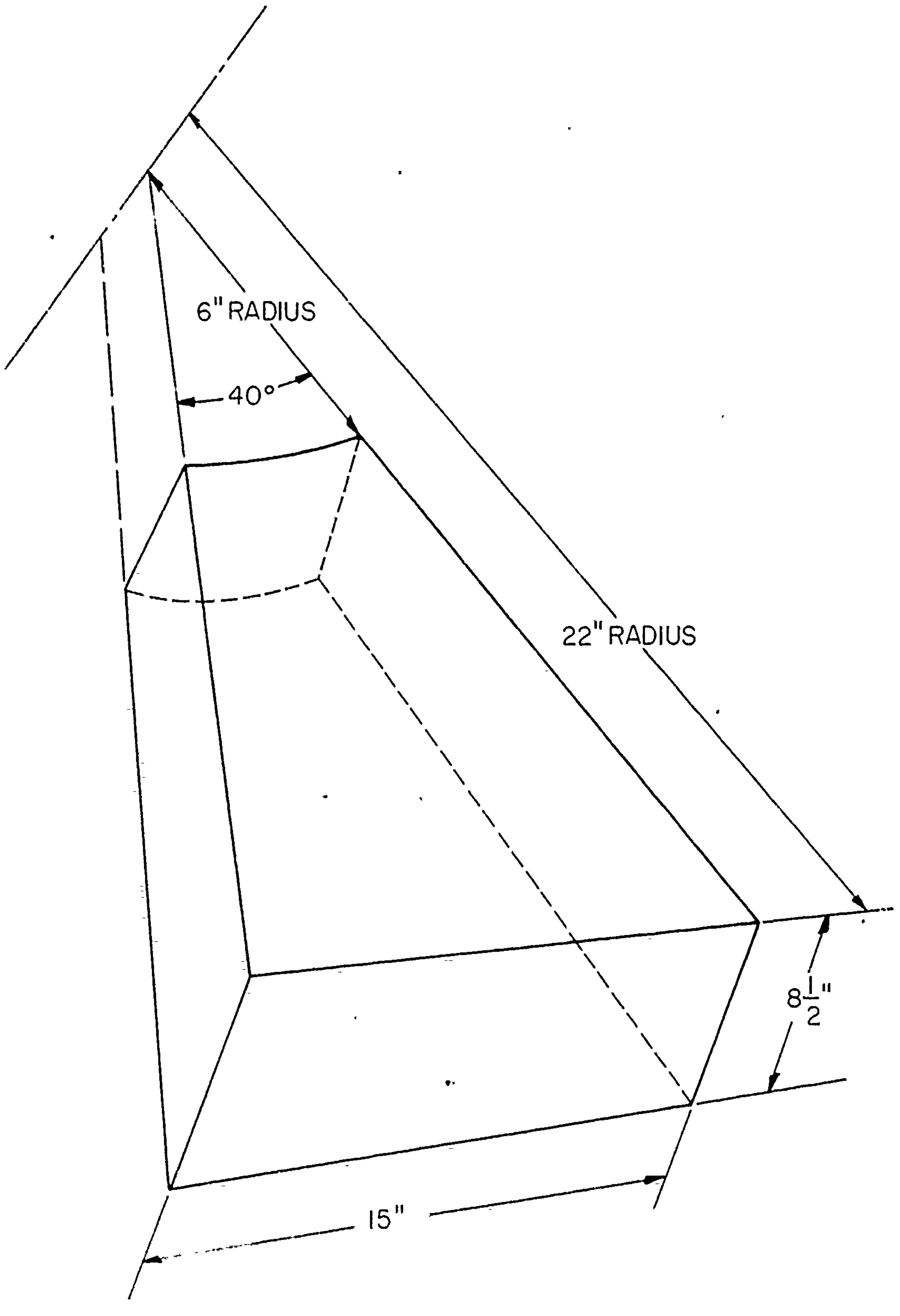

FIG. 2 SATELLITE PHOTOMETER COMPARTMENT

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particle bombardment in the extraterrestrial environment must be considered.

Optical Noise

The detection of stray light which enters the field-of-view of the optical system must be reduced to a minimum. This stray light may arise by virtue of internal reflection of external sources such as the sun and from internal sources such as calibration light.

Spectral Resolution

The photometer is designed to measure radiation at various desired spectral intervals. The optical system design must satisfy the requirements of the desired spectral resolution.

4.3.2 Photometer Optical System Analysis and Design

Basic Geometry

Another optical design parameter is the detector photocathode size, which has been chosen 1/2 in. in diameter. The simple geometric characteristics of the photometer optical system are shown in Figure 3. The detector size and desired field-of-view determine that a 3.59 in. focal length is required. With a 4 in. aperture, this will require an f/0.9 lens. The above aperture and focal length represent a 58° total angular aperture. Finally, this geometric situation indicates that the maximum angle of incidence to the normal of the photocathode surface is about 32°. The last is important in evaluating the effect of convergent radiation with respect to the spectral isolation as formed by an interference filter.

Aberrations

The geometrical characteristics of the above described lens indicates that it will be afflicted with various types of aberrations. The large angular aperture will undoubtedly exhibit spherical aberration and longitudinal chromatism. The relatively wide field-of-view will show, to some extent, monochromatic aberrations

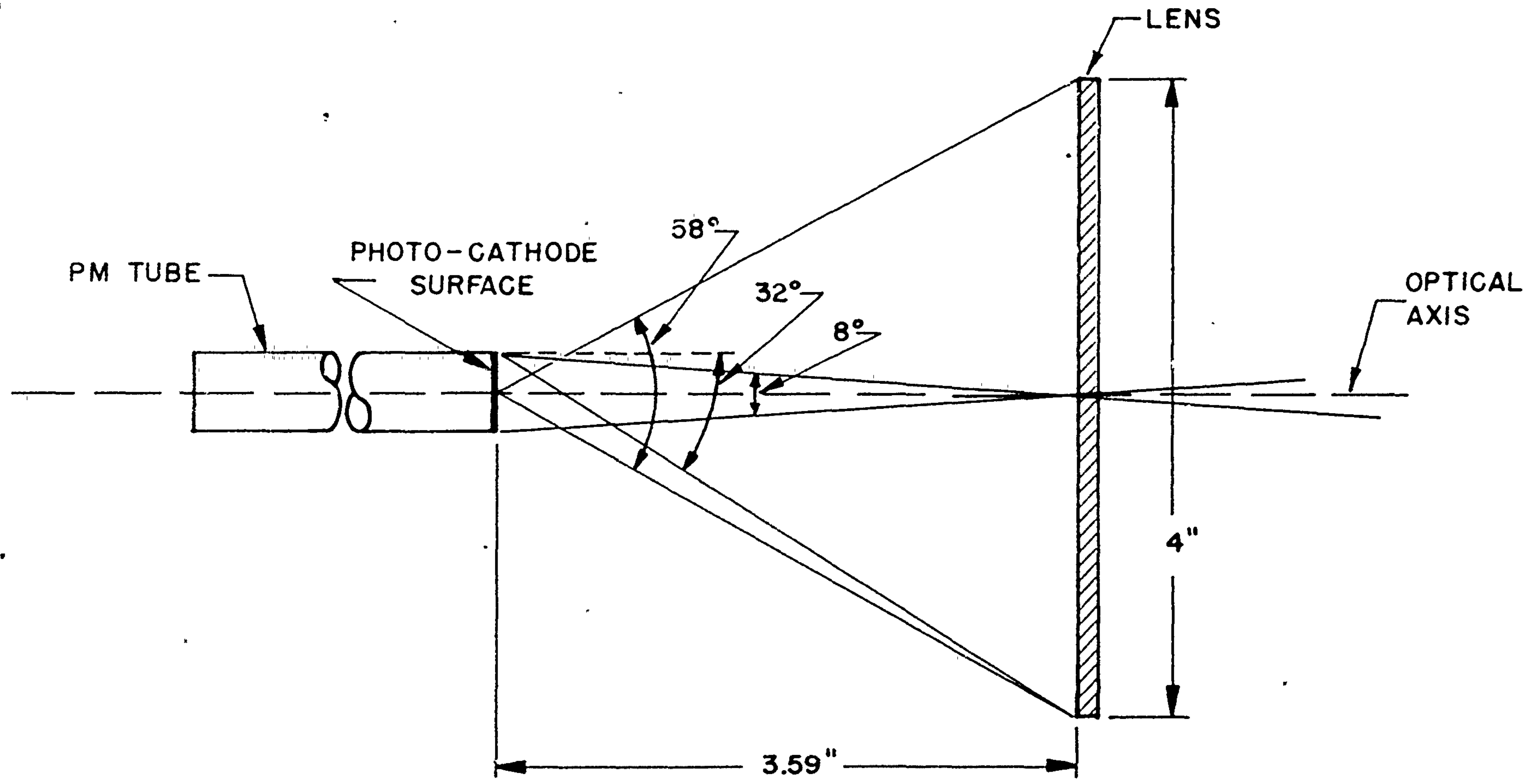

FIG. 3 GEOMETRICAL CHARACTERISTICS OF PHOTOMETER OPTICAL SYSTEM

(coma, astigmatism, curvature, and distortion) and lateral chromatism. Some of the above defects can be corrected by the proper lens design but not all at once. However, it is important to note that the satellite photometer is not an image-forming optical instrument. Its purpose is to collect radiant energy in a specified solid angle by means of a specified aperture and bring it to a photocathode surface. Thus, the aberrations will be a consideration in the lens design only with respect to their effect upon the field-of-view determination.

Types of Optical Systems

Some of the optical systems and configurations available for the satellite photometer are shown in Figure 4. Figure 4a is a conventional double convex refractor and 4b is a refracting Fresnel lens which is used for weight reduction purposes. Figures 4c and 4d are the same as a and b but with a 45° mirror to alter the overall configuration of the optical system. Figure 4e is a reflecting system of the Hale type and 4f is a modified Cassegranian reflector with a flat secondary. Figures 4g and 4h are Newtonian and Herschelian (off-axis) respectively.

The various optical configurations of Figure 4 are compared in Table I with respect to their utility in the satellite photometer. However, before discussing the table it is important to list the parameters upon which the table is based. These are:

1. A four inch aperture is required
2. An effective focal length of 3.59 in. is required.
3. The photocathode diameter is 1/2 in.
4. The photomultiplier is 5 in. long and 3/4 in. diameter

Table I compares the various optical systems whose designs are based upon the above fixed parameters. The column entitled "Rating" is

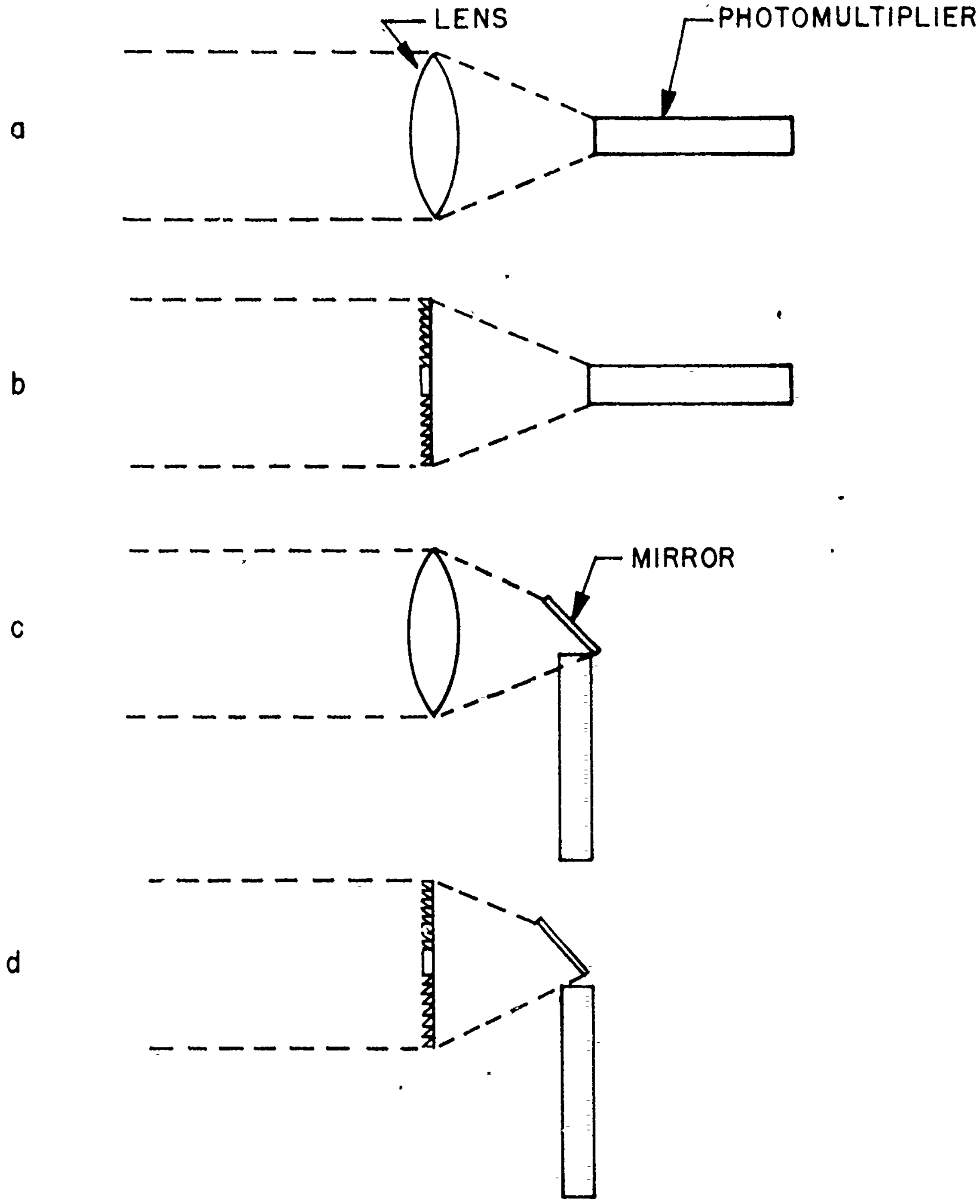

FIG. 4 VARIOUS OPTICAL SYSTEMS

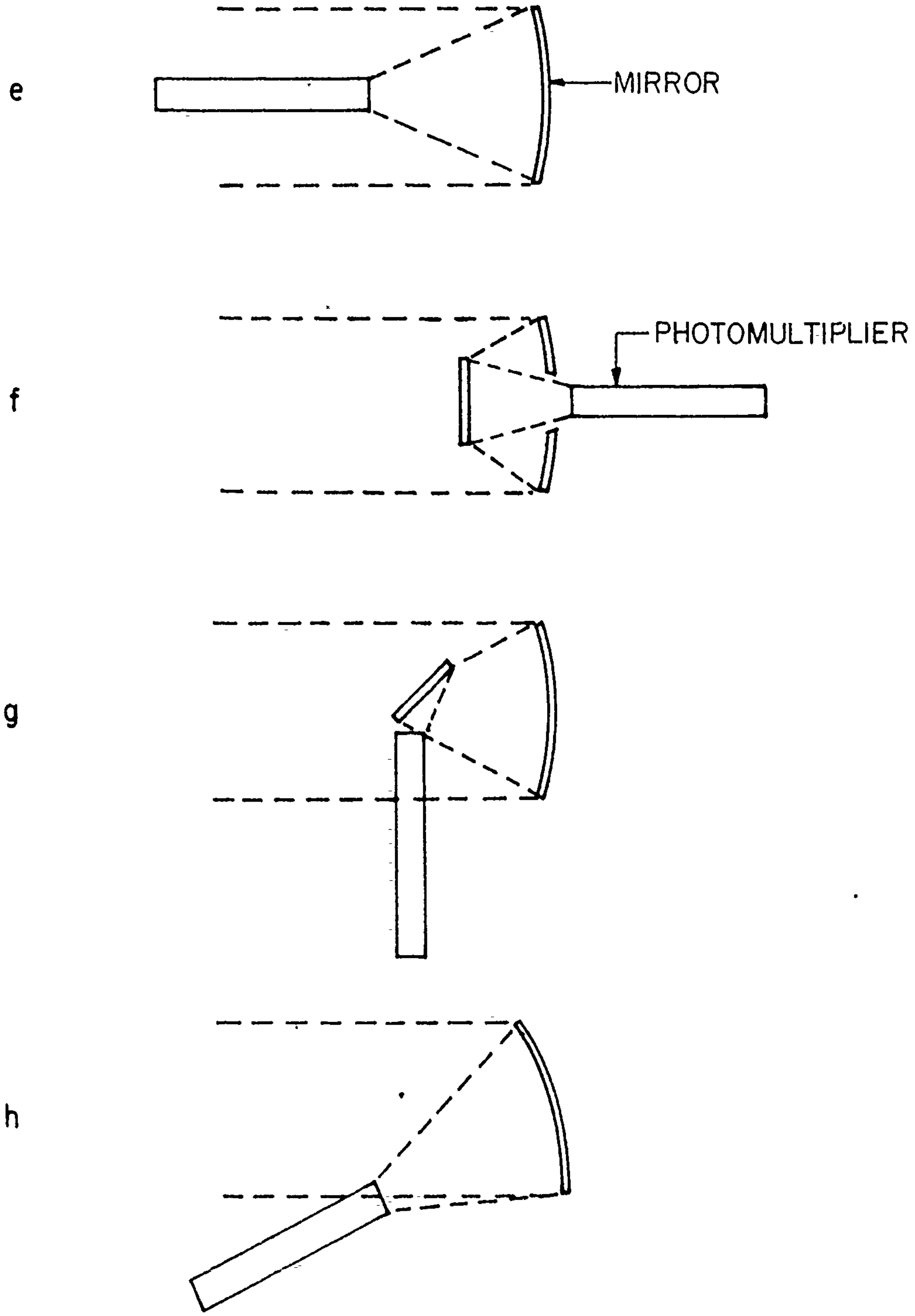

FIG. 4 VARIOUS OPTICAL SYSTEMS (continued)

TABLE I COMPARISON OF VARIOUS OPTICAL SYSTEMS FOR SATELLITE PHOTOMETER

Fig.	Optical System	Material	Estimated[1] Weight (Lbs)	Transmission[2] Optical	Geom.[3]	Total	Volume (In^3)	Max. Dimen (In)	Rating
a	Refractor-Double Convex	Glass	0.82	92	100	92	144.9	19 x 4 x 4	0.78
		Plastic (Lucite)	0.34	90	100	90	144.9	19 x 4 x 4	1.80
b	Refractor-Fresnel	Glass	0.25	92	100	92	144.9	19 x 4 x 4	2.5
		Lucite	0.10	90	100	90	144.9	19 x 4 x 4	6.2
c	Refractor- DBL CX w/ 45° Mirror	Glass (Metal 45°)	0.86	85	87	74	144.9	14 x 7 x 4	0.59
		Lucite (Metal 45°)	0.38	83	87	72	144.9	14 x 7 x 4	1.3
d	Refractor-Fresnel w/45° mirror	Glass (Metal 45°)	0.29	85	87	74	144.9	14 x 7 x 4	1.8
		Lucite (Metal 45°)	0.14	83	87	72	144.9	14 x 7 x 4	3.6
e	Reflector-Hale	Metal	0.035	92	96	88	126	10 x 4 x 4	20.2
		Glass (1/4"thick)	0.322	98	96	94	126	10 x 4 x 4	2.3
f	Reflector Modified Cassegranian	Metal	0.055	92	64	59	128	15 x 4 x 4	8.5
		Glass	0.342	98	64	63	128	15 x 4 x 4	1.4
g	Reflector-Newtonian	Metal	0.055	92	74	68	128	10 x 7 x 4	9.7
		Glass	0.342	98	74	72	128	10 x 7 x 4	1.7
h	Reflector-Herschelian(Off-Axis)	Metal	0.035	92	100	92	128	10 x 7 x 4	20.7
		Glass	0.322	98	100	98	128	10 x 7 x 4	2.4

1. Does not include weight of supporting frame.
2. The values are averaged over the visible region. The geometrical transmission is that due to occulations of the particular optical configuration (secondary mirror, etc).
3. Includes the lens, detector, the space between the lens and detector (where applicable) and an arbitrary 10 in. long cylinder in front of the lens to provide space for light traps or baffles which will reduce optical noise (stray light).

developed as follows: Three important optical system parameters for the satellite photometer are weight, volume, and transmission. The rating values are the total transmission divided by the weight and volume considerations of a particular optical configuration. The method of rating is arbitrary and serves only as an indication of the utility of an optical design for the photometer application.

The conclusions that may be drawn from Table I are:

1. Reflecting optics are more desirable than refractors.
2. Metal reflectors are more desirable than coated glass.
3. The Herschelian and Hale configuration are more desirable than the Newtonian and modified Cassagranian.

With respect to the choice between the Herschelian and Hale configuration, the former is better suited for the satellite photometer application because it allows objects such as filter, shutter, and calibrating sources to be introduced in the system (directly in front of the photomultiplier tube) without blocking the incoming radiation. Figure 5 shows the proposed optical system configuration and its relation to the satellite compartment.

Optical Noise

The term optical noise (stray light) may be defined as any radiation that impinges upon the photocathode which does not arise from sources within the field of view of the photometer. Perhaps the greatest source of stray light is the sun; although not in the instrument's field of view, if close to the optical axis it may illuminate the photocathode by means of successive specular and/or diffuse reflections. Since the purpose of the photometer is to measure low light levels, the stray light must be kept to a minimum if the measurements are to have any meaning.

The design philosophy for the reduction of stray light is to prevent the sun's radiation from impinging directly on the pri-

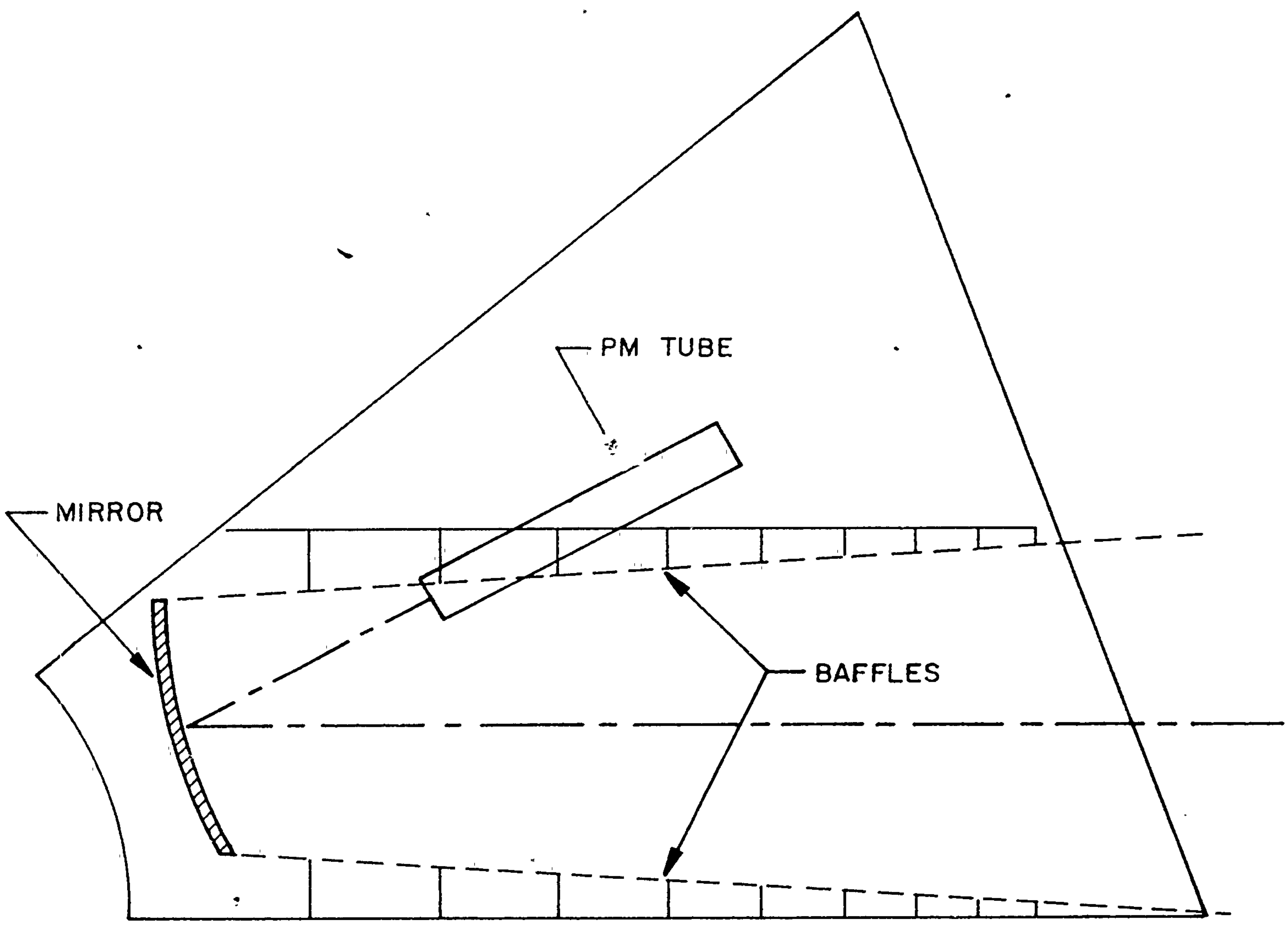

FIG. 5 OPTICAL SYSTEM CONFIGURATION (HERSCHELIAN) FOR SATELLITE PHOTOMETER

mary mirror or lens surface of the photometer while the instrument is in operation. If solar energy does illuminate a part of the lens (but not directly the photocathode) the photometer should not be operated; if operated, it should be realized that the data could be erroneous due to scattered light from the lens. In order to shield the lens from solar (or other) radiation a baffle or set of baffles should be used in front of the lens. These baffles can be of two basic types as shown in Figure 6. The arrangement shown in Figure 6a consists of an opaque and highly absorbing cylinder that does not enter the field of view of the photometer. The minimum sun-optical axis angle where solar illumination of the lens does not occur is θ. Figure 6b shows a set of concentric cylindrical baffles that are placed in the field of view. Here, the minimum sun-optical axis angle (θ) equals the field of view.

The advantage of the arrangement of Figure 6a is that the photometer never "sees" the baffles. This is desirable since no baffle material will be 100 percent absorbing. Also, this arrangement allows a constant angular response for the photometer as shown in Figure 7a. The main disadvantage of this arrangement is that the minimum sun-optical axis angle is always larger than the field of view and will not allow the photometer to operate very close to the sun. The value of θ will depend upon the aperture, field of view, and length of the baffle and may be expressed as

$$\theta = \tan^{-1} \left[(A/L) + \tan \phi/2\right]$$

where

A = aperture

L = baffle length

ϕ = field of view.

The main advantage of the configuration shown in Figure 6b is that the minimum sun-optical axis angle equals the field of view and the photometer may operate (theoretically) very close to the sun. However, the baffles placed in the field of view reduce the

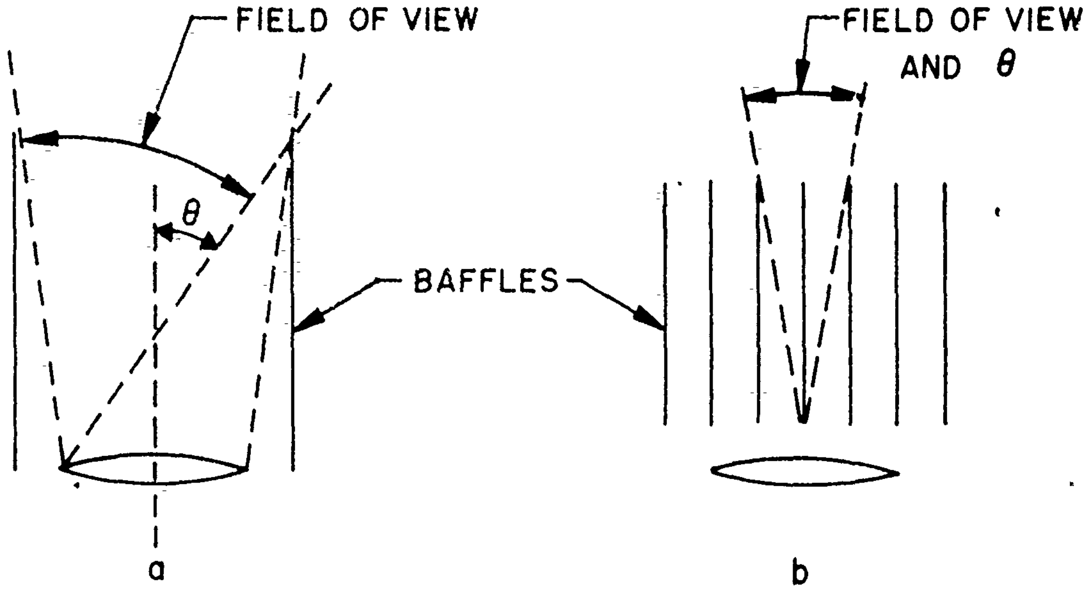

FIG. 6 BAFFLES FOR SOLAR SHIELDING

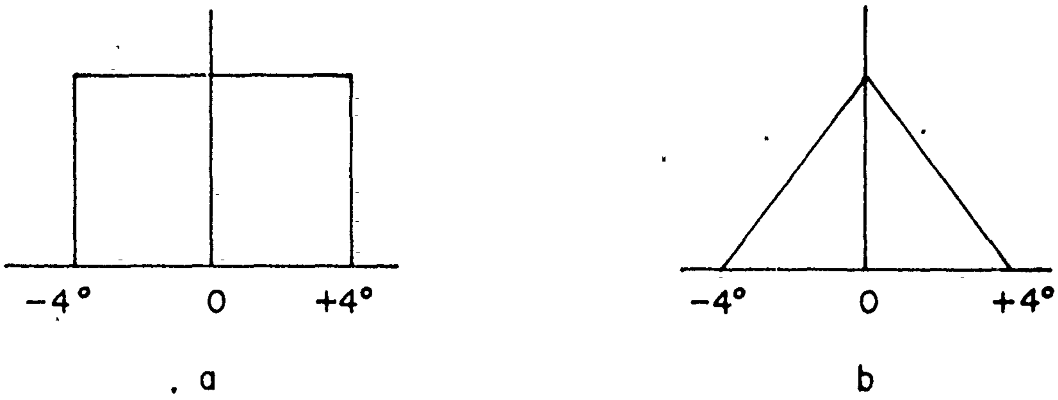

FIG. 7 PHOTOMETER RESPONSE DUE TO SHIELDING AS A FUNCTION OF ANGULAR DISTANCE FROM OPTICAL AXIS

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speed of the photometer and, probably more serious from a data reduction point of view, the baffles produce a non-uniform angular response (Figure 7b). Thus, it is proposed to use the configuration shown in Figure 6a for the photometer shielding. Since one cannot obtain 100 percent absorbing material for the shield it is also proposed to use additional baffles as shown in Figure 5 to reduce the probability of significant solar radiation from impinging upon the lens. These additional baffles will not be in the field of view of the instrument.

Spectral Filtering

Since the mission of the photometer is to measure radiance at various spectral intervals, it is necessary to investigate the effect of the optical design upon the performance of the spectral filter. In order to conserve weight and space, the filter should be introduced into the optical system where the light beam cross section is a minimum, immediately in front of the PM tube. Unfortunately, convergent radiation is associated with this position in the optical system. This will not adversely affect the performance of colored glass or gelatin filters but will affect the spectral resolution as defined by an interference filter. From the basic geometry described in Section 3.1 the maximum angle of convergence is about 32^{o} for the detector and f/0.9 lens. Table II shows the performance of a sample interference filter in parallel light and under the above conditions.

TABLE II COMPARISON OF INTERFERENCE FILTER IN PARALLEL AND CONVERGENT RADIATION

	Parallel	f/0.9 Lens
Peak Wavelength	650 μ	638 μ
Halfwidth	10 μ	34 μ

As can be seen, the spectral resolution has been degraded by about a factor of three. The peak wavelength has been shifted but this may be compensated for by proper initial filter specification. It is felt that the above spectral resolution should not adversely affect the overall photometer operation. If this spectral resolution is not satisfactory, then the convergence can be reduced by different optical design.

4.3.3 Proposed Optical System Features

The following are specifications and features of the proposed satellite photometer optical system:

1. Total field of view - 8°
2. Mirror - off-axis ($\pm 15^{\circ}$) paraboloid
3. Aperture - 4 in.
4. Focal length - 3.59 in.
5. Size - Optical system (including detector, filter wheel, and baffles) occupies about 400 in^3
6. The optical system will operate to within 12° of a bright object such as the sun without giving erroneous values.
7. The angular response of the optical system is flat over the full 8° field of view
8. The filter wheel will accommodate three filters, a shutter and a calibration position
9. The mirror is located so as to maximize its lifetime by minimizing the effects of particle erosion.
10. The transmission of the optical system(exclusive of the filter) is about 92 percent.

5. ROCKET PHOTOMETER

5.1 Purpose of Rocket Photometer

The rocket photometer should be considered as a forerunner of the satellite photometer and the purpose of the two instruments is thus directly inter-related. The satellite photometer mission as currently envisioned is twofold: (1) to measure the extragalactic light, and (2) to measure the atmospheric night airglow from space.

It is felt that the rocket photometer should not be concerned with the airglow measurements for the following reasons:

a. We already have fairly good measurements of the general intensity radiance levels involved (particularly at 5577A^o).

b. Rocket photometers have already been flown for the purpose of measuring the night airglow.

c. The prime purpose of the test is to prove the satellite instrument for the astronomical experiment.

The purpose of the rocket photometer should be:

1. To get an order of magnitude estimate of the total radiance of extragalactic light.
2. To get a very broad estimate of the spectral distribution of the extragalactic light.
3. To evaluate the photometer design with respect to the space environment.
4. To evaluate the photometer design with respect to the rocket vehicle.

5.2 Rocket Photometer Specifications

In order to carry out the above mission of the rocket photometer, the instrument should satisfy the following specifications:

a. It should be capable of pointing at the galaxy. This specification concerns the attitude of the optical axis with respect to the rocket and the attitude of the rocket with respect to the galaxy. For a first approximation it might be better if the photometer looked at the galactic poles since there are fewer stars to subtract from the data.

b. The altitude of the rocket should be such that the photometer data is not influenced by the night airglow, the sunlit earth or its atmosphere.

c. The angular response of the photometer should be as flat as possible to simplify data reduction procedures.

d. The photometer should have an optimum light gathering capability commensurate with final optical design and vehicle consideration.

e. The photometer should incorporate two or three wide band spectral filters (possibly Wratten) if vehicle consideration will permit.

f. Design configuration and philosophy of the rocket photometer should relate to that of the proposed satellite photometer. This cannot be accomplished completely because of differences between rocket and satellite in such factors as the vehicle, altitude, duration at altitude, attitude (and time history), acceleration at launch, vehicle space availability, power availability and telemetry bandwidth.

g. Finally, the attitude of the optical axis (and thus, the rocket vehicle) with respect to the galaxy must be known during the photometer data-taking portions of the flight. This will directly affect the final data accuracy.

5.3 Rocket Photometer Design

The design of the rocket photometer should embody the characteristics of ruggedness, lightweight, small total volume and high optical speeds. A suggested design is shown in Figure 8 and has the following characteristics which assume that the rocket will be launched at night and will not cross the solar horizon.

a. A lightweight off-axis parabolical mirror will be used for the optical system.

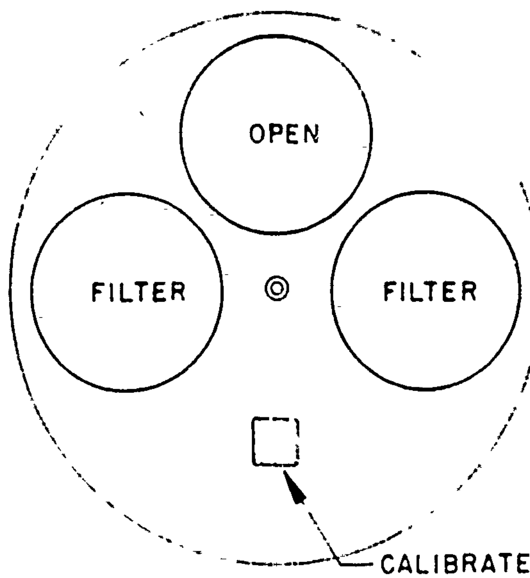
b. No field-of-view baffling is provided which saves photometer weight and volume.

c. No intensity control or mechanical shutter is provided since the photometer will be flown at night. The photometer should be protected from bright light on the pad prior to the launch if voltage is applied to the PM tube. This can be accomplished by an opaque "dark slide" which is a part of and conforms to the rocket skin and can be ejected or retracted when the rocket attains altitude. This will also provide aerodynamic protection to the photometer.

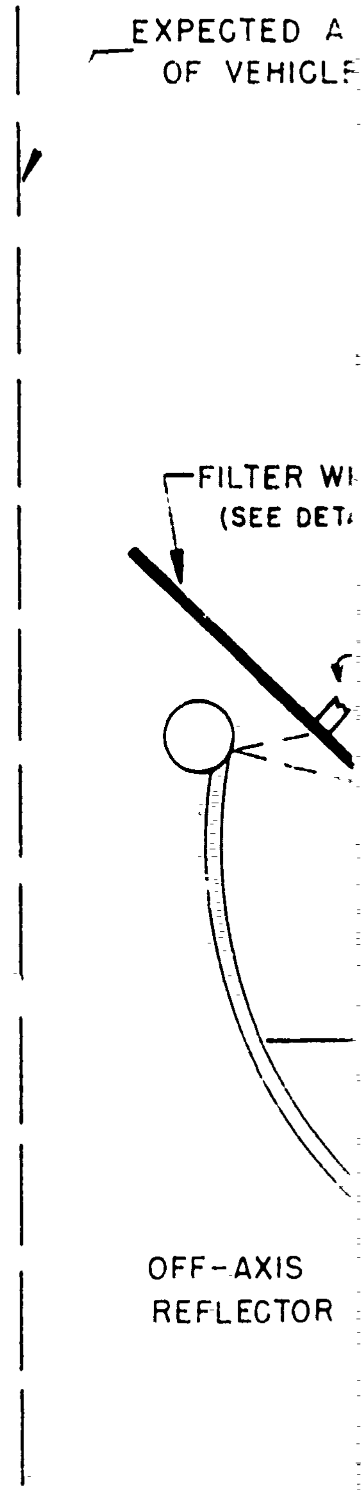
d. The total field of view is roughly 20°.

e. The volume of the optical system, filter wheel and PM tube is about 100 in^3.

f. The filter wheel has four positions, calibrate, open, and two filter positions. The calibrate is merely a radioactive light source placed on an opaque position of the wheel. The open or no-filter position is important in obtaining the order-of-magnitude total extragalactic radiance. The two filters should be broad band types such as a Wratten No. 34 (3300-4700A) and No. 57 (4800-5900A).



DETAIL OF FILTER WHEEL



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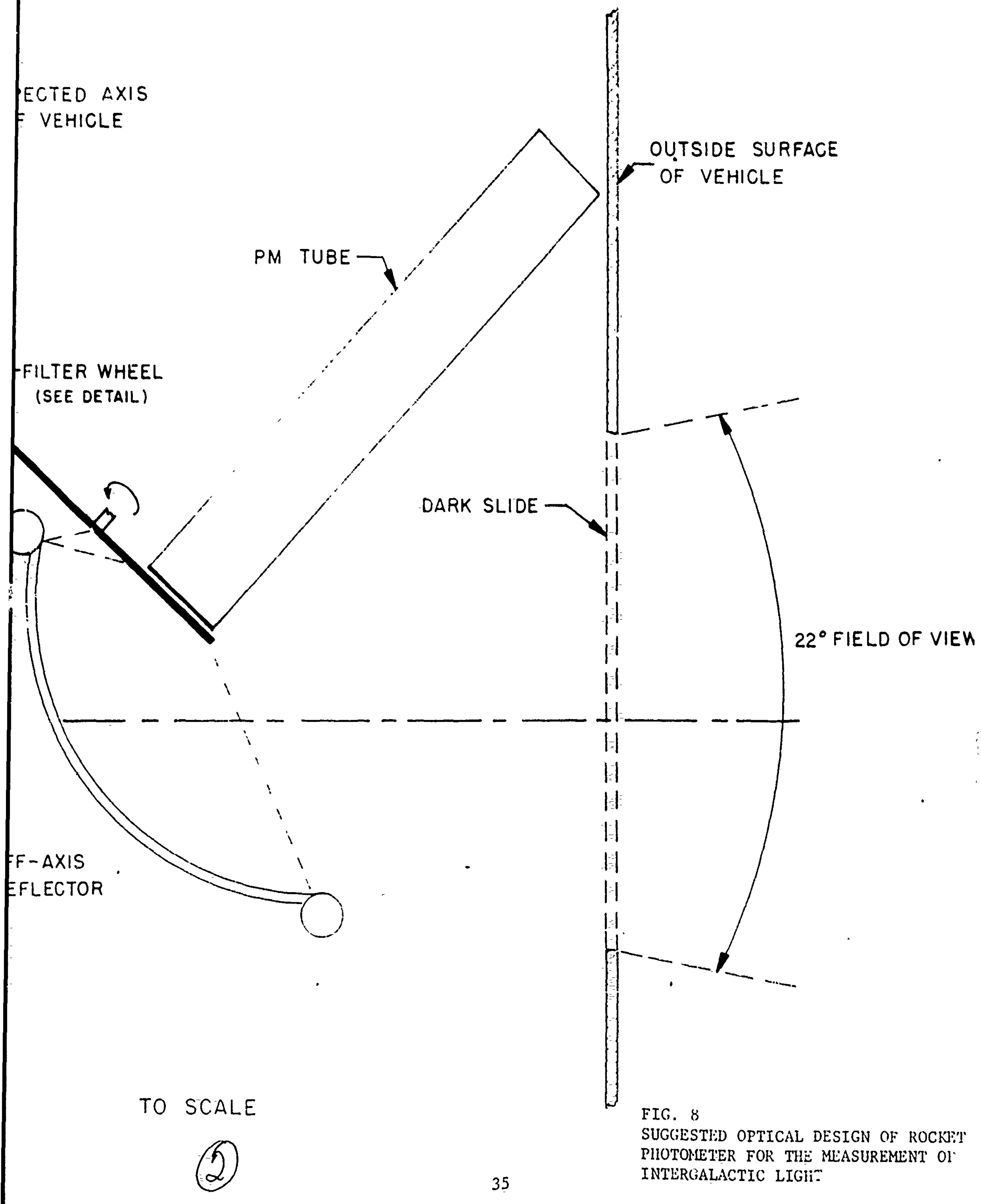

FIG. 8
SUGGESTED OPTICAL DESIGN OF ROCKET PHOTOMETER FOR THE MEASUREMENT OF INTERGALACTIC LIGHT

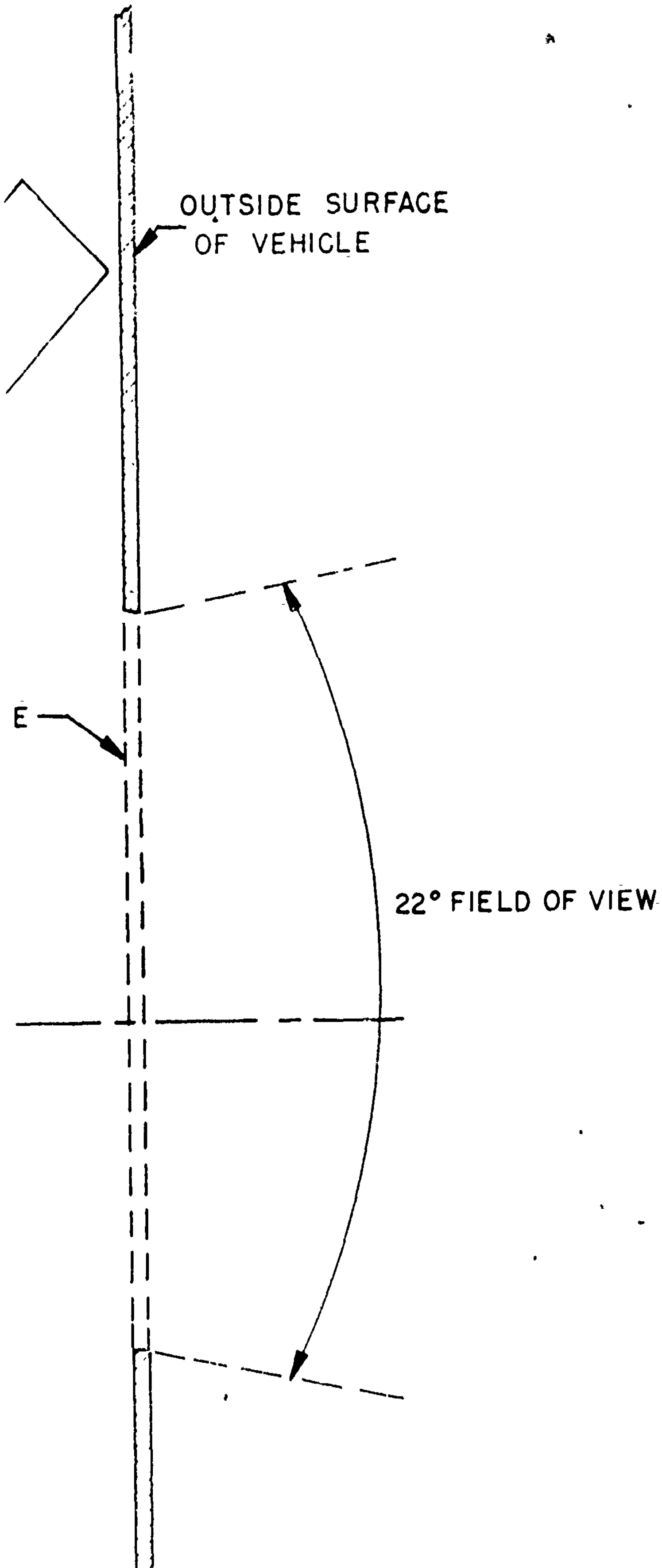

FIG. 8
SUGGESTED OPTICAL DESIGN OF ROCKET
PHOTOMETER FOR THE MEASUREMENT OF
INTERGALACTIC LIGHT

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5.4 Details to be Determined for Rocket Photometer Design

1. Volume and configuration of space available for photometer.
2. Maximum altitude of rocket.
3. Time spent above certain altitudes.
4. Attitude of vehicle.
5. Spin rates (if any).
6. Possibility of night launchings.
7. Location of photometer with respect to vehicle.
8. Available power.
9. Telemetry bandwidth.
10. Acceleration of launch.

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2. W. A. Baum, "A Fundamental Cosmological Experiment for the Artificial Satellite", The Publication of the Astronomical Society of the Pacific, 68: 118-120, April 1956.

3. C. T. Butler, W. A. Baum,"The Measurement of Integrated Extra-Terrestrial Radiation by Means of a Satellite-Borne Photometer," Publication No. 151, Jet Propulsion Laboratory, Pasadena, California, February 11, 1959.

APPENDIX A

ALTERNATE OPTICAL SYSTEM FOR SATELLITE PHOTOMETER

A feasible optical design is shown in Figure A-1.

The primary element is a 4" off-axis parabola which focusses the sky through a filter wheel and onto a field lens. The field lens images the primary on the 1/2" diameter cathode of a photomultiplier tube.

The field lens insures that all light falling on the primary is spread uniformly over the cathode, regardless of the distribution in the field of view, and hence that the phototube reads the true integrated power, unaffected by cathode hot spots.

Detectivity

The ability of the system to detect faint illumination will depend upon the ultimate noise level of the phototube. If the noise equivalent input power of the phototube is known, as well as the parameters of the optical system it is possible to calculate a noise equivalent scene brightness by

$$L = \frac{4W}{a\theta^2} \sqrt{\Delta f}$$

where
L = n.e. scene brightness - lamberts
W = n.e.p. of phototube - lumens
a = area of objective - cm^2
θ = field of view - radians
Δf = system bandwidth - cps

A calculation of L for a one cycle bandwidth for two types of photomultiplier is given below, assuming an objective area of 78.5 cm^2 and a field angle of .14 radian (8^o).

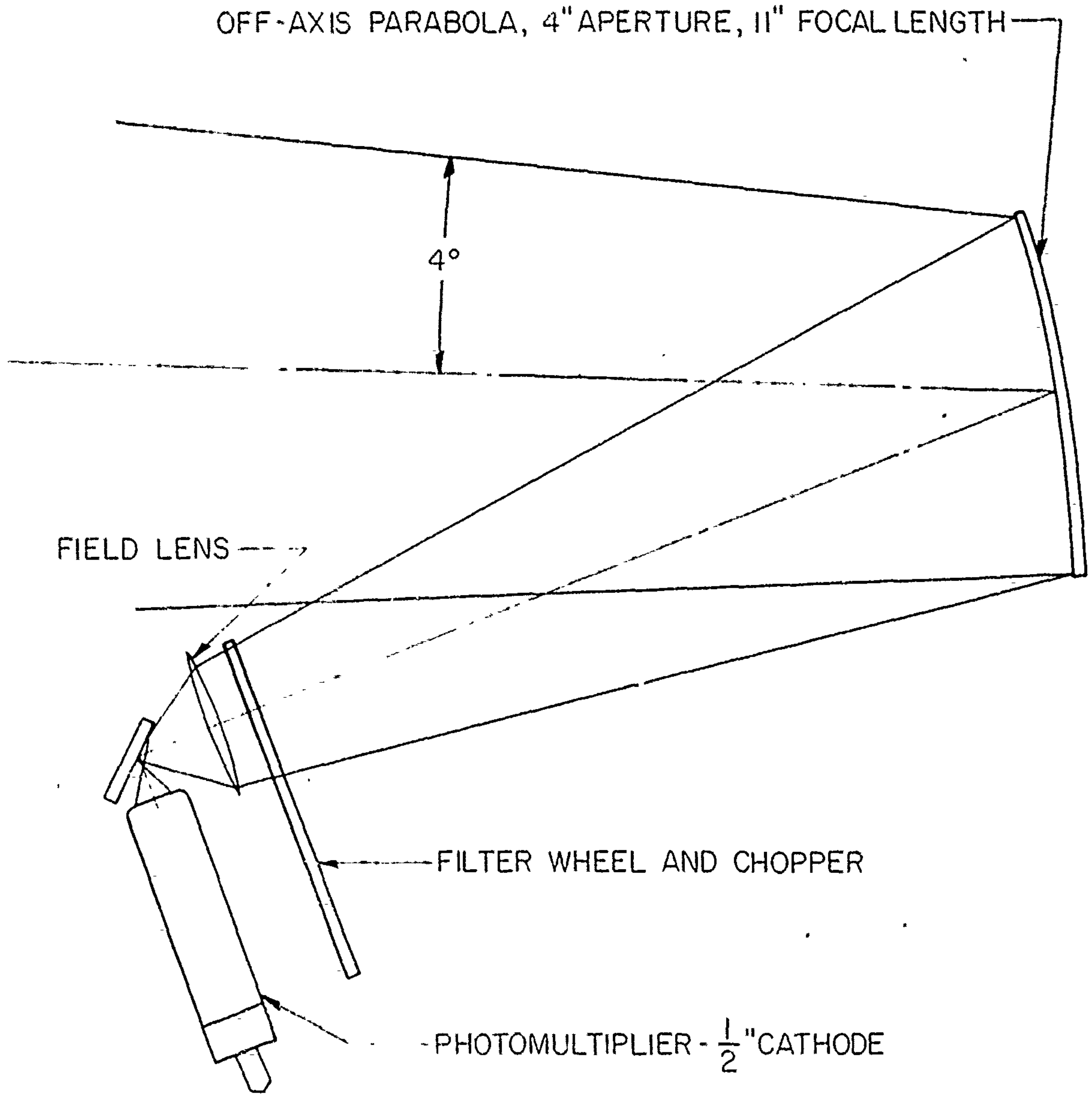

FIG. A-1 OPTICAL DESIGN

Tube	Cathode	W	Lamberts	Candles/cm^2
RCA 7767	1/2" S-11	3×10^{-12}	7.7×10^{-12}	2.4×10^{-12}
BMI 9558B	1.7" S-20	1.5×10^{-13}	3.8×10^{-13}	1.2×10^{-13}